

Overlooked model uncertainties may misinform forest management strategies

Victor, Jérôme, Isabelle, and more?

Abstract: Forests play a major role in mitigating climate change, but increasing threats to forests from climate change have heightened the importance of managing these systems. Robust forecasts of forest composition with increasing climate change are critical to this aim, but are currently highly variable. To help guide management in the face of this variability and understand where we can most rapidly reduce uncertainty through improved models, we compare over XX ecological models and climate scenarios in forecasts for forests across Europe. Our approach considers a gradient of more mechanistic (‘process-based’) to correlative models of species distributions to find that uncertainty in ecological models can drive more variation than vastly different climate scenarios (e.g., SSP2 vs. SSP5), but also areas with relatively consistent projections [give overview of these and say that this could reduce uncertainty in how to manage for these areas]. [Maybe something on using existing range data leads to more pessimistic forecasts?] Our results highlight a new way to approach ecological forecasting that better identifies areas of higher certainty and, conversely, the areas where managers will need more diversified approaches and where more ecological study may be most useful.

1 Main

2 Forests are key to pursuing climate change mitigation policies and achieving carbon neutrality^{1,2}.
3 Yet, forests are increasingly under pressure. In Europe, temperatures are rising twice as fast as
4 the global average³, and unprecedented pulses of tree mortality have been reported in the last
5 decade⁴. As a result, some European forests are becoming net CO₂ sources^{5,6}, due to decreased
6 growth^{5,7}, larger burned areas^{8,9}, and increased pest- and drought-induced dieback^{6,10,11}. Forest
7 managers are facing unprecedented challenges, as they must address current threats while also
8 promoting long-term adaptation to climate change. In this context of high uncertainty, better
9 guidance and evidence-based projections are needed to implement successful strategies.

10 Given the diversity of predictive ecological models, the challenge of providing practical in-
11 sights for forest management is even greater. Different models, ranging from correlative to more
12 mechanistic approaches, may provide highly divergent projections^{12–15}. While it remains un-
13 clear under which conditions one approach is more reliable than another¹⁶, most projections still
14 rely on a limited set of models^{17–20}, ultimately increasing the risk of policy and management
15 failures²¹. We often lack a robust estimation of uncertainty and a comprehensive understanding
16 of what drives differences between projections²². Given the urgency of climate change, we must
17 incorporate the diversity of models and merge across ecological and climatological models to
18 provide a complete picture of both the threats and opportunities for forests.

19 Gaining a better understanding of where uncertainties originate and how they relate is crucial
20 to identify opportunities to address policy-relevant questions^{23,24}. Species shifts are predicted
21 to have major impacts on timber production and on the forest economic sector^{18,19}. Forest
22 managers need to know whether the current species will be able to tolerate future climate
23 conditions, whether they can rely on its natural regeneration, or whether they should capitalize
24 on new species opportunities. If the main driver of variation across projections is the different

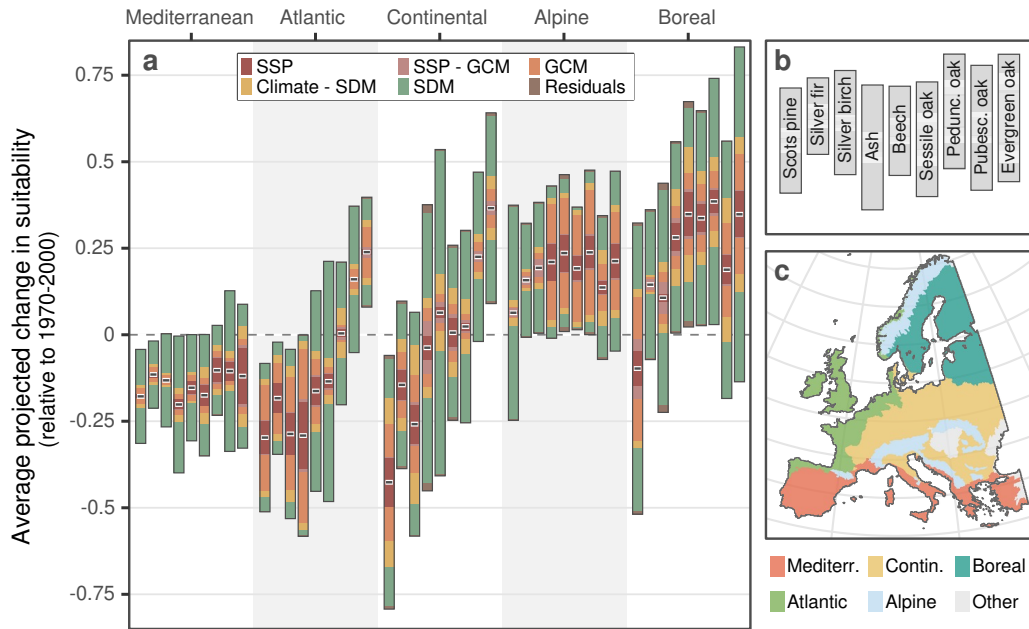


Figure 1

ecological models, even more than different global emissions scenarios, it becomes critical to encompass the full range of models. Failing to do so could lead to overly confident predictions about which species will or will not be able to survive in future climates, ultimately leading to counterproductive or even detrimental forest management decisions.

To understand the level of confidence we can place in predictions requires a framework that account for all the various components of climatological and biological uncertainties, including socio-economic scenarios, global climate models, ecological models, down to the species level. To this aim, we combined over 1,500 projections of forest tree species distributions, incorporating a wide range of models, from more mechanistic (‘process-based’) to correlative models. Fully accounting for our current level of knowledge about future climate states and species functioning allows us to quantify the contribution of each component to the total variation across projections. This approach represents a significant advancement over previous studies, which overlooked large portions of uncertainty, and will lead to better informed decision-making to improve the resilience of forests.

Results and discussion

Our dataset included 9 tree species, both deciduous and coniferous, adapted to diverse climatic conditions across Europe. We simulated their suitability from 1970 to 2100, at a 0.1° spatial resolution, using a diverse set of ecological models spanning different hypotheses and calibration methods. We used 10 different future climate simulations, based on 2 forcing scenarios and 5 global climate models with different climate sensitivities.

Across species, ecological models drive more variation than vastly different climate scenarios (Figure 1). They consistently represent the main source of uncertainty across major European biomes (explaining between 42.9% and 63.9% of the variation between projections), with the exception of the Alpine biome. At the species-level, across all biomes, the differences between ecological models is also the main source of uncertainty for all the species considered here, and represents between 40% and 62% of the total uncertainty on average. One of the striking example is the climatic suitability change of sessile oak in the Atlantic region, where this species represents an important cultural and economic value, and for which more than 80% of the uncertainty in climate change impact projections was due to variations among ecological models.

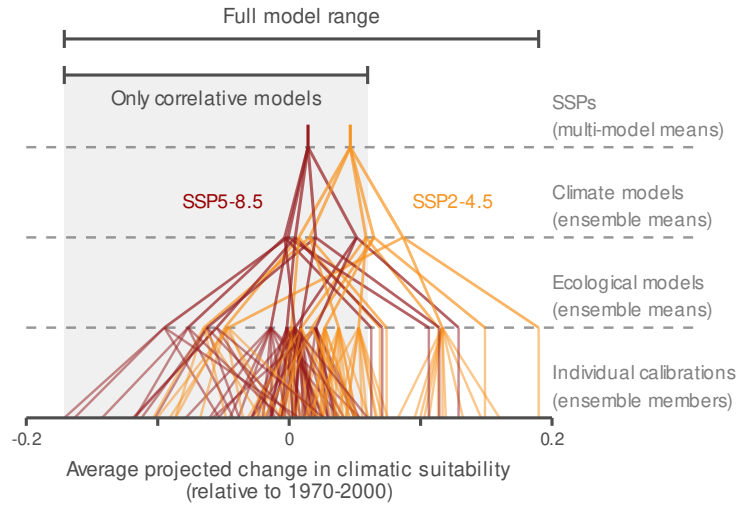


Figure 2: Temporary figure

Failing to account for a broad range of ecological models severely underestimate projection uncertainty, and ultimately lead to incorrect trend estimates (Figure 2). Considering only correlative models would have misled to an overestimation of the contribution of climate projections (forcing scenarios, climate models, and their two-way interaction) to the total projection uncertainty in all regions, except the Mediterranean. In particular, divergence between climate models would have appeared to contribute as much as ecological models to projection uncertainty (on average, 36.6% and 37.5%, respectively). When accounting for more diverse ecological models, as done in our study, the uncertainty introduced by different ecological models (51.0% on average) becomes greater than that introduced by climate models (19.9% on average) for all the species. One of the key challenges for reducing uncertainty thus remains at the biological and ecological levels, even before considering the broad variations across future climate projections.

Our results also revealed that the divergence between ecological model projections followed a regular pattern. Models calibrated using current species range data consistently predict greater extinctions than models calibrated using experimental data (Figure 3). Current distribution data may capture only a portion of the climatic niche of a species, underestimating the range of conditions where it could survive^{25,26}. These discrepancies between models can significantly alter country-level projections, and impact national strategies derived from them. In France for example, beech showed an average suitability decrease of $-X (\pm Y)$ in 2090 when considering only models entirely calibrated with current species distribution data. But this decreasing trend vanish once a broad range of models is accounted for ($X \pm Y$). Relying on a narrow set of models—especially derived from the same calibration process—undermines the robustness of projections²¹, and may ultimately bias decisions towards intensive intervention strategies (e.g. introduction of species outside their native range), potentially overlooking alternative strategies.

Despite large uncertainties, comparing diverse models improve prediction robustness and enable to identify areas with relatively consistent projections that differ in terms of future climate risks and levers of action to address them (Figure 4). Around the Mediterranean Basin, the models consistently predict less favorable climatic conditions for the species we considered here. In areas where most species are threatened, forest managers may consider introducing more drought-tolerant species. Along the Atlantic margin, the suitability of most species is also projected to decrease, except for the two Mediterranean species—pubescent and evergreen oaks—which could replace less adapted temperate species such as beech²⁷. Mechanistic model projections are less pessimistic for deciduous oaks and beech in France, suggesting that some better-adapted populations could survive if the existing standing genetic variation is maintained and promoted by forest managers²⁸. Additionally, adapting management practices, such as decreasing stand density to limit competition for water, could support their long-term survival

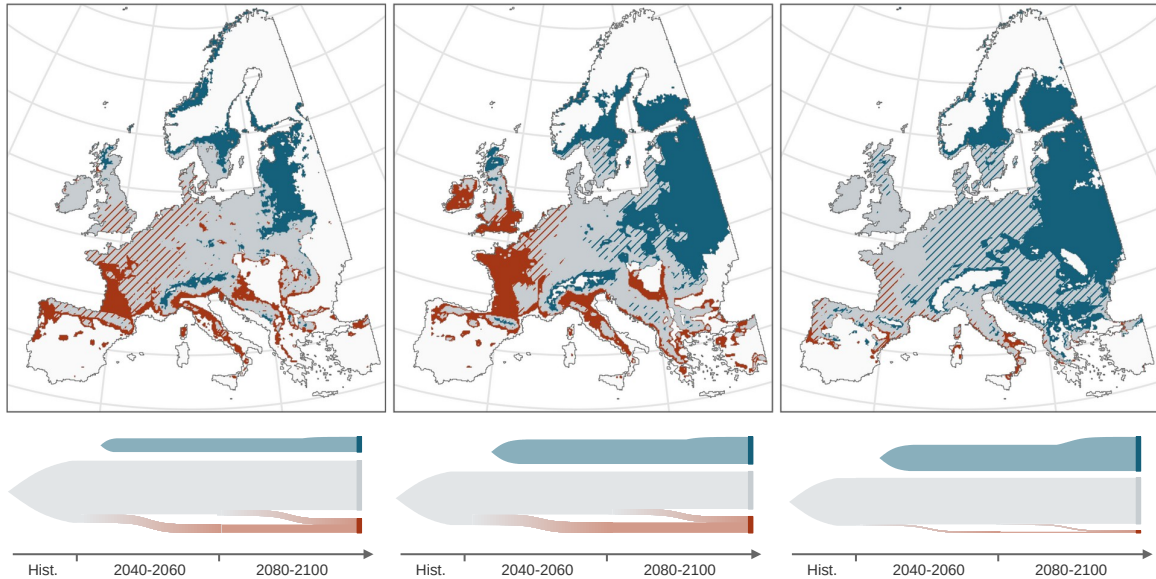


Figure 3: Temporary figure

to drought events²⁹. A large part of the Continental biome exhibit less clearer trends, as well as mountainous regions at the transition between Mediterranean and Continental/Atlantic climates (Pyrenees, Massif Central, Balkans). Yet, looking at divergence across projections still provide important insights into species and locations most likely to experience significant changes in future climatic conditions. Models agree on a lower suitability for Scots pines (with uncertainty driven more by climatic models and scenarios, 45.7%, than by ecological models, 30.8%), which is a commercially very important species [cite] in several countries of Central Europe (Poland, Eastern Germany, Czech Republic, Belarus). Projections also suggest that temperate deciduous species (e.g. beech, deciduous oaks) will be less affected by climate change, despite high uncertainties due to high divergence among ecological models (between 45.7 and 75.4% of the total uncertainty). A key lever of action in this region is the diversification of tree species, as well as increasing genetic diversity within populations, to mitigate the risks associated with uncertain future conditions³⁰⁻³³. Promoting uneven-aged stands could also enhance forest stability by improving structural complexity and buffering against climate extremes^{34,35}.

Finally, boreal biomes in Scandinavian and Baltic countries are projected to get an overall increase of climatic suitability. These include Finland and Sweden, two very important forestry countries in terms of wood stock, added value, and forest-based workforce. Forests in these regions are dominated by two conifers species, Scots pine and spruce, favoured by commercial forest management. The lack of experimental data prevented us from making mechanistic model projections for spruce, but uncertainty for Scot pine future suitability was very high. As models consistently project that temperate deciduous trees will become more competitive at the northern margin of their range, the extending growing season could offer an opportunity to convert pure coniferous stands into mixed forest to increase their resilience³⁷. Decisions ne peuvent que être prise en parallèle d'un développement filière économique pour especes decidues.

The implications of these results extend beyond European forests. L'importance des incertitudes raise questions about the robustness of existing projections, and highlight that further advances are necessary to provide rigorous policy-relevant projections. Looking ahead: a call to action for the scientific community...

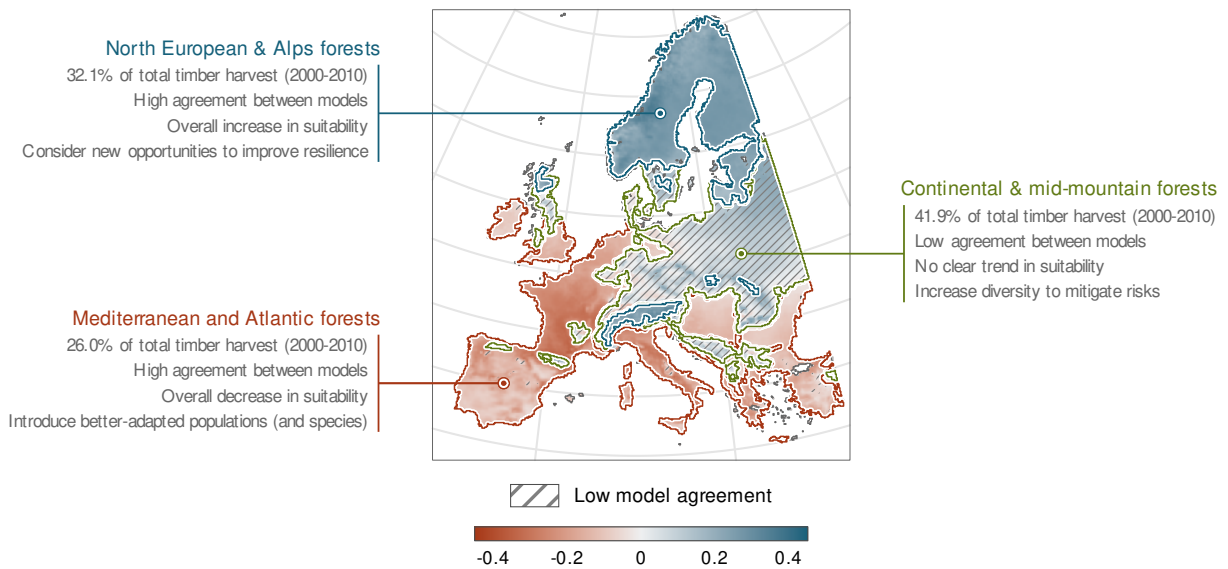


Figure 4: Temporary figure

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